

# **Uncertainty Analysis for Broadband Solar Radiometric Instrumentation Calibrations and Measurements: An Update**

**Preprint**

D.R. Myers, I.M. Reda, S.M. Wilcox, and  
T.L. Stoffel

*To be presented at the World Renewable Energy  
Congress VIII  
Denver, Colorado  
August 28–September 3, 2004*



**NREL**

**National Renewable Energy Laboratory**  
1617 Cole Boulevard, Golden, Colorado 80401-3393  
303-275-3000 • [www.nrel.gov](http://www.nrel.gov)

Operated for the U.S. Department of Energy  
Office of Energy Efficiency and Renewable Energy  
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

## NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at <http://www.osti.gov/bridge>

Available for a processing fee to U.S. Department of Energy  
and its contractors, in paper, from:

U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831-0062  
phone: 865.576.8401  
fax: 865.576.5728  
email: <mailto:reports@adonis.osti.gov>

Available for sale to the public, in paper, from:

U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
phone: 800.553.6847  
fax: 703.605.6900  
email: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
online ordering: <http://www.ntis.gov/ordering.htm>



# **Uncertainty Analysis for Broadband Solar Radiometric Instrumentation Calibrations and Measurements: An Update**

D. Myers, I. Reda, S. Wilcox, T. Stoffel

National Renewable Energy Laboratory, 1617 Cole Blvd, Golden CO 80401

## **Abstract**

Emphasis on solar renewable energy technologies in the 1970's, and the concern about the Earth's radiation balance related to the possibility of climate change in the 1990's raised the importance of broadband solar radiation measurements. In parallel, standardized methods of uncertainty analysis and reporting have been developed. Historical and updated uncertainties are based on the present international standardized uncertainty analysis method. Despite the fact that new and sometimes overlooked sources of uncertainty have been recently identified, uncertainty in broadband solar radiometric instrumentation remains at 3% to 5% for pyranometers, and 2% to 3% for pyrhemliometers. Improvements in characterizing correction functions for radiometer data may reduce total uncertainty. We analyze the theoretical standardized uncertainty sensitivity coefficients for the instrumentation calibration measurement equation and highlight the single parameter (thermal offset voltages), which contributes the most to the observed calibration responsivities.

## **Introduction**

Uncertainty requirements vary for assessing solar radiation resources for solar energy systems, or investigating climate change. For renewable energy assessment, uncertainty of a few percent may be adequate. One watt per square meter ( $\text{W/m}^2$ ) uncertainty is needed to determine radiative forcings in climate change. Uncertainty in the calibration of pyrhemliometers (measuring the solar direct beam), and pyranometers (measuring the diffuse sky and total sky, or global [combined direct and diffuse] radiation) determines the uncertainty in measurements they report

## **Radiometer Calibrations**

The World Radiometric Reference (WRR) is the standard for solar radiometers [1, 2], and embodies the International System of Units (SI) of solar irradiance. Romero et al. [3] showed equivalence of better than  $\pm 0.05\%$  between WRR and the SI radiation scale. The WRR is transferred with an uncertainty of  $\pm 0.3\%$  to national reference absolute cavity radiometers (ACR) every five years at the World Radiation Centre in Davos Switzerland [4, 5]. Pyrhemliometer responsivities ( $R_s$ , output signal per stimulus unit) are derived by direct comparisons with reference ACRs traceable to WRR [4]. Pyranometer responsivities are often derived from the "component summation" technique, where a reference global irradiance ( $G$ ) is derived from an absolute cavity radiometer beam measurement ( $B$ ) and shaded pyranometer (diffuse) measurement ( $D$ ) using  $G = B \cos(z) + D$ .

Responsivity ( $R_{sd}$ ) for a diffuse-measuring reference pyranometer is derived in a shade-unshade calibration using  $R_{sd} = (U-S)/[B \cos(z)]$  where  $U$  and  $S$  are the unshaded and shaded output voltages from the sensor,  $z$  is the zenith angle, and  $B$  is measured by

an ACR[6] Procedures for this calibration are described in the American Society for Testing and Materials Standard E-913 [6]. NREL proposed shade-unshade pyranometer calibration using an average responsivity at 45° zenith angle for three instrument azimuth angles to integrate over geometric response variations [7]. A modification includes a continuously shaded, or control pyranometer, and 60° rotation angles [8]. Regression fits of responsivities to zenith angle,  $R_s(z)$  determine six  $R_s(45^\circ)$ , the mean of which is used for the reference diffuse (shaded pyranometer) in a component summation calibration.

## Uncertainty Analysis

Measurements only approximate the quantity being measured, and are incomplete without a quantitative uncertainty. The Guide to Measurement Uncertainty (GUM) of the International Bureau of Weights and Measures [9] is the accepted guide for measurement uncertainty. The GUM defines Type A uncertainty values as derived from statistical methods, and Type B sources as evaluated by "other means", such as scientific judgment, experience, specifications, comparisons, or calibration data.

Every element of a measurement system contributes elements of uncertainty. When a result,  $R$ , is functionally dependent upon several  $i=1, \dots, n$  variables,  $x_i$ , the familiar propagation of error formula  $U^2 = \sum (\partial_{x_i} R \cdot e_{x_i})^2$  is used.  $U$  is the uncertainty in the resultant,  $e_{x_i}$  is the estimated uncertainty in variable  $x_i$ , and  $\partial_{x_i} R$  is the partial derivative of the response  $R$  with respect to variable  $x_i$ , called the sensitivity function for variable  $x_i$ .

Previously [10,11] pyranometer calibration uncertainty treated sources of uncertainty in terms of "random" and "bias" types. Total uncertainty  $U$  was computed from:  $U^2 = \sum (\text{Bias})^2 + \sum (2 \cdot \text{Random})^2$ . The resulting uncertainty in calibration of pyranometer responsivity and field measurements was 2.4%, and 5%, respectively. The GUM replaces the factor of two with a "coverage factor",  $k$  and  $U^2 = \sum (\text{Type B})^2 + \sum (k \cdot \text{Type A})^2$ . For small ( $n < 20$ ) samples,  $k$  may be selected from the student's  $t$ -distribution [12].  $U$  is the "Expanded Uncertainty", and  $k$  is usually in the range of 2 to 3, for confidence intervals of 95% and 99%, respectively [12].

## Recently Identified Uncertainty Sources: Thermal Offset

World Climate Change Research Program participants and others [13, 14] have identified thermal offsets in thermopile pyranometers that measure diffuse radiation with all-black sensors [15, 16]. The offsets appear as negative signals at night, and clear sky diffuse irradiances lower than expected with pure Rayleigh scattering [16]. Cold junctions of "all-black" thermopiles are in a different thermal environment than absorbing junctions, while in black-and-white sensors, reference and absorbing junctions are in a similar thermal environment. The latter radiometers have low ( $\sim 1$  to  $2 \text{ W/m}^2$ ) offsets and produce more accurate diffuse measurements [17].

## Sensitivity Functions

Reference diffuse radiometer responsivity uncertainty,  $U_{\text{shade}}$ , computed from the propagation of error formula for the shade-unshade calibration equation is:

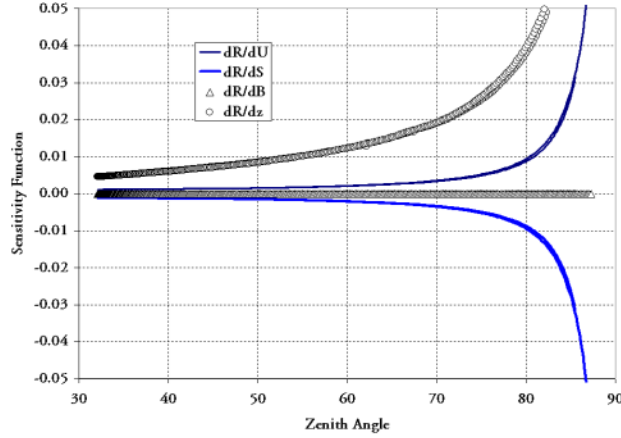
$$U_{\text{shade}}^2 = (\partial_U R_s \cdot e_U)^2 + (\partial_S R_s \cdot e_S)^2 + (\partial_B R_s \cdot e_B)^2 + (\partial_Z R_s \cdot e_Z)^2$$

where  $e_U$  is the uncertainty in unshaded voltage, etc. For the component summation

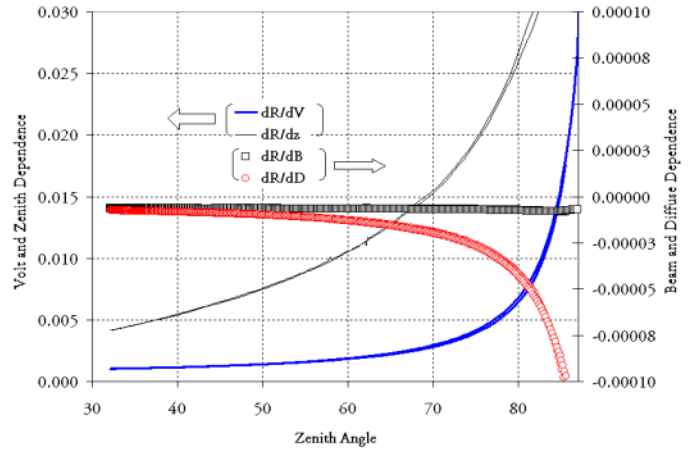
equation, the propagation of error formula becomes:

$$U_{\text{sum}}^2 = (\partial_U R_s * e_U)^2 + (\partial_D R_s * e_D)^2 + (\partial_B R_s * e_B)^2 + (\partial_z R_s * e_z)^2$$

For a data set of pyranometer voltages, beam and (black and white) diffuse irradiances, figure 3a and 3b show sensitivity functions for each of the calibration types.



**Fig. 3a. Sensitivity functions for shade-unshade calibration.** Note sensitivity to shade (negative line) and unshade (positive line) voltages are mirror image of each other. Greatest sensitivity is to zenith angle (circles). Negligible sensitivity to beam uncertainty.



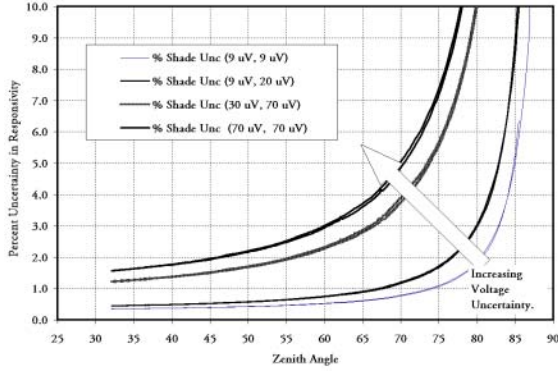
**Fig. 3b. Sensitivity functions for component summation calibration.** Sensitivity to beam (square) and diffuse (circle) irradiances are much less (right scale) than to voltage (heavy line) and zenith angle (light line) (left scale).

Total uncertainties depend on the product of sensitivity functions and  $e_i$ . The most important contributions come from the  $e_V$ ,  $e_U$  and  $e_S$ , *which must include estimates of the thermal offset* as well as data logger measurement uncertainty (typically < 10 uV). For an (all-black sensor) pyranometer responsivity of 7.0 mV per 1000 Wm<sup>-2</sup> a 70 uV offset corresponds to an irradiance of -10 W/m<sup>-2</sup>. Figures 4a and 4b show the percent uncertainty in responsivity for increasing uncertainty in voltage measurements for  $e_B = 4.0 \text{ Wm}^{-2}$ ,  $e_z = 0.06^\circ$ ,  $e_D = 2.0 \text{ Wm}^{-2}$  (black and white sensor). Note the component summation technique has relatively lower uncertainties, because there is only the one voltage component, as opposed to two in the shade-unshade technique.

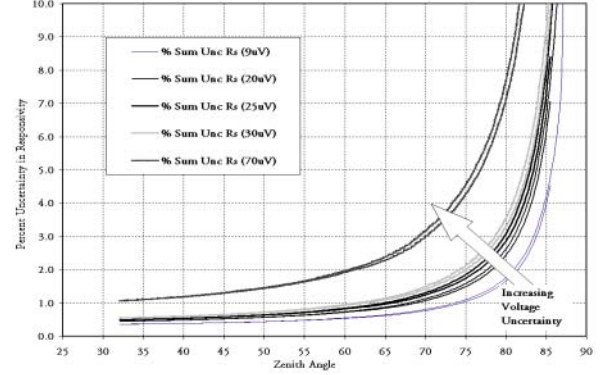
## Responsivity Functions

Figure 5 shows the responsivity of a pyranometer versus zenith angle using NREL component summation calibration [18]. Analysis of the uncertainty in each pyranometer calibration responsivity *point* in figure 5 is summarized in table 1. A responsivity function derived from such data with the *offsets embedded in the result* can be used to retrieve the most accurate irradiance from a pyranometer.

The far right curve in figure 4b assumes  $e_V$  = data logger uncertainty (9 uV) only, and "ignores" the offset voltage, which is "built into" the calibration result. The expanded uncertainty with  $k=2$  for each point in figure 5 is 0.7%. This is the smallest uncertainty that can be expected of a pyranometer under conditions identical to the calibration conditions.



**Fig. 4a.** Total Uncertainty in shade-unshade calibrations versus zenith angle for various uncertainties in voltage measurement with fixed beam ( $4 \text{ Wm}^{-2}$ ) and z angle ( $0.06^\circ$ ) uncertainty. Arguments in parenthesis are uncertainty in shade unshade voltages, respectively



**Fig. 4b.** Total uncertainty in component sum calibrations as a function of zenith angle for various uncertainties in voltage measurement (in parenthesis), and fixed beam ( $4 \text{ Wm}^{-2}$ ), zenith angle ( $0.06^\circ$ ), and diffuse ( $2 \text{ Wm}^{-2}$ ) uncertainty.

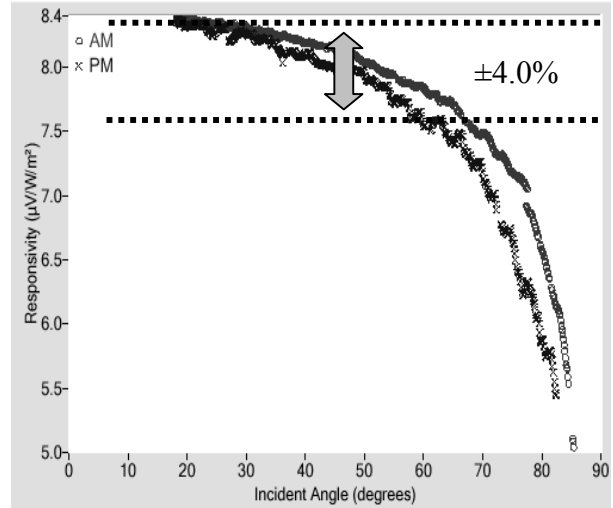
The responsivity for a particular zenith angle,  $m$ , at the time of measurement,  $R_s(m)$ , can be obtained from a fit to the calibration response curve, using forty-six  $2^\circ$  wide zenith angle intervals, of the form:

$$R_s(z)_{AM/PM} = \sum_{i=0}^{i=46} a_i \cdot \cos^i(z)$$

where  $a_i$  are 46 coefficients for each morning and afternoon set of  $z$ . With this approach, uncertainty of  $\pm 1.5\%$  in measured pyranometer data can be achieved. Using a responsivity at a given  $z_0$ ,  $R_s(z_0)$ , the uncertainty in a measurement of global irradiance will change as the difference between  $R_s(z_0)$  and  $R_s(m)$  changes, and may grow to more than 10% for zenith angles sufficiently different.

## Conclusion

Sensitivity functions for shade-unshade and component summation pyranometer calibration techniques show that uncertainties in signal voltages, including thermal offset voltages, affect  $R_s(z)$  the most, when beam, diffuse, and zenith angle errors are minimal. Either calibration can map geometric and thermal response. The range of deviations in  $R_s(z)$  produce uncertainty in measured data that is highly dependant on the responsivity chosen. The best measured data ( $U \sim 1.5\%$ ) is that using  $R_s(z)$  for the zenith angle at the time of the measurement. That responsivity can be obtained from a fit of  $R_s(z)$ . Otherwise, uncertainty of 3% to 5% or more, can occur in measured global solar radiation data.



**Fig. 5.** Pyranometer responsivity versus solar zenith angle. Dotted lines are +4% and -4% away from mean  $R_s(45^\circ)$ .

Table 1. Uncertainty for each measured responsivity point in figure 5.

Source	Type B %	2*Type A %	Combined (RSS)
WRR Ref. Cav ( $\pm 4 \text{ Wm}^{-2}$ )	0.300	0.200	0.50
Compute Z, Cos(Z) ( $\epsilon_z < 0.06^\circ$ )	0.005	0.010	0.02
Diffuse Pyran Cal ( $\pm 2 \text{ Wm}^{-2}$ )	0.200	0.125	0.25
Temperature Response ( $\Delta T < 10^\circ \text{ C}$ )	0.050	0.100	0.21
Data Logger ( $\pm 9.0 \text{ uV}$ )	0.090	0.005	0.09
Cavity Wind effects	0.025	0.025	0.17
Spectral effects	0.010	0.010	0.02
<b>TOTAL</b>	<b>0.376 %</b>	<b>0.516 %</b>	<b>0.638 % (k=2)</b>

#### REFERENCES

- [1] Zerlaut G.A. "Solar Radiation Measurements: Calibration and Standardization Efforts." Duffie, J.A., ed. *Advances in Solar Energy*. Vol. 1, Boulder, CO: American Solar Energy Society, Inc., 1983; pp. 19-59.
- [2] WMO. "OMM No. 8 guide to Meteorological Instruments and Methods of Observation." 5th ed. Vol. 8, Geneva, Switzerland: Secretariat of the World Meteorological Organization, 1983.
- [3] Romero, J.; Fox, N.P.; Frohlich, C. "Improved Comparison of the World Radiometric Reference and the Si Radiometric Scale." *Metrologia*; 1996; **32**(6): pp. 523-524.
- [4] Reda, I. *Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric*. NREL/TP-463-20619 1996. Golden, CO: National Renewable Energy Laboratory, 1999.
- [5] WMO. *International Pyrhemliometer Comparison VIII*. Working Report No 188. Davos, Switzerland World Meteorological Organization, 1996.
- [6] ASTM. *Standard Method for Calibration of Reference Pyranometers with Axis Vertical by the Shading Method*. ASTM E913-97. West Conshohocken, PA : American Society for Testing and Materials, 1997.
- [7] Reda, I.; Myers, D. *Calculating the Diffuse Responsivity of Solar Pyranometers*. NREL/TP-560-26483. Golden, CO: National Renewable Energy Laboratory, 1999.
- [8] Reda, I.; Stoffel, T.; Myers, D. "A Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." *Solar Energy*; 2003; **74**: pp. 103-112.
- [9] BIPM. *Guide to the Expression of Uncertainty in Measurement*. Geneva, Switzerland: Published by ISO TAG 4. ISBN number is 92-67-10188-9, 1995. 1995 BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML.
- [10] Myers, D.R. "Application of a Standard Method of Uncertainty Analysis to Solar Radiometer Calibrations." *Solar 89, Proceedings of 1989 Annual Conference of The American Solar Energy Society, Denver, CO*. Boulder, CO: American Solar Energy Society, 1989.
- [11] Myers, D.R.; Emery, K.A.; Stoffel, T.L. "Uncertainty Estimates for Global Solar Irradiance Measurement used to Evaluate PV Device Performance." *Solar Cells*; 1989; **27**(1-4): pp. 455-565.
- [12] Taylor, B.N.; Kuyatt, C.E. "Guidelines for Evaluation and Expressing the Uncertainty of NIST Measurement Results." *NIST Technical Note 1297*. Boulder, CO: National Institute of Standards and Technology, 1993.
- [13] WMO. *World Meteorological Organization Scientific Plan for World Climate Research Programs*. WCRP-2. Geneva, Switzerland World Meteorological Organization, 1984.
- [14] Houghton, J.T.; et al., ed. *The Science of Climatic Change*. IPCC (Intergovernmental Panel on Climate Change). Cambridge, United Kingdom: Cambridge University Press, 1996.
- [15] Gulbrandsen, A. "On the Use of Pyranometers in the Study of Spectral Solar Radiation and Atmospheric Aerosols." *Journal of Applied Meteorology*; 1978; **17**: pp. 899-904.
- [16] Dutton, E.G.; et al., "Measurement of Broadband Diffuse Solar Irradiance Using Current Commercial Instrumentation With a Correction for Thermal Offset Errors." *Journal of Atmospheric and Oceanic Technology*; 2001; **18**(3): pp. 297-314.
- [17] Stoffel, T.L.; et al., "Current Issues in Terrestrial Solar Radiation Instrumentation for Energy, Climate and Space Applications." *Metrologia*; 2000; **37**(5): pp. 399-401.
- [18] Myers, D.R.; Stoffel, T.L.; Wilcox, S.; Reda, I.; Andreas, A. Recent Progress in Reducing the Uncertainty in and Improving Pyranometer Calibrations." *American Society of Mechanical Engineers (ASME) Journal of Solar Energy Engineering*; 2002; **124**: pp. 44-50.

<b>REPORT DOCUMENTATION PAGE</b>			<i>Form Approved</i> OMB NO. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 2004		3. REPORT TYPE AND DATES COVERED Conference Paper
4. TITLE AND SUBTITLE Uncertainty Analysis for Broadband Solar Radiometric Instrumentation Calibrations and Measurements: An Update; Preprint				5. FUNDING NUMBERS  PVP4.7102
6. AUTHOR(S) D.R. Myers, I.M. Reda, S.M. Wilcox, T.L. Stoffel				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER  NREL/CP-560-36201
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161				12b. DISTRIBUTION CODE
13. ABSTRACT ( <i>Maximum 200 words</i> ) The measurement of broadband solar radiation has grown in importance since the advent of solar renewable energy technologies in the 1970's, and the concern about the Earth's radiation balance related to climate change in the 1990's. In parallel, standardized methods of uncertainty analysis and reporting have been developed. Historical and updated uncertainties are based on the current international standardized uncertainty analysis method. Despite the fact that new and sometimes overlooked sources of uncertainty have been identified over the period 1988 to 2004, uncertainty in broadband solar radiometric instrumentation remains at 3% to 5% for pyranometers, and 2% to 3% for pyrhemometers. Improvements in characterizing correction functions for radiometer data may reduce total uncertainty. We analyze the theoretical standardized uncertainty sensitivity coefficients for the instrumentation calibration measurement equation and highlight the single parameter (thermal offset voltages), which contributes the most to the observed calibration responsivities.				
14. SUBJECT TERMS Broadband solar radiation; uncertainty analysis; international standardized uncertainty analysis method				15. NUMBER OF PAGES
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified		18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified		19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified
				20. LIMITATION OF ABSTRACT  UL